Variation in large-volume landslides controlled by glacial stratigraphic architecture, NW Washington

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USGS science for a changing world

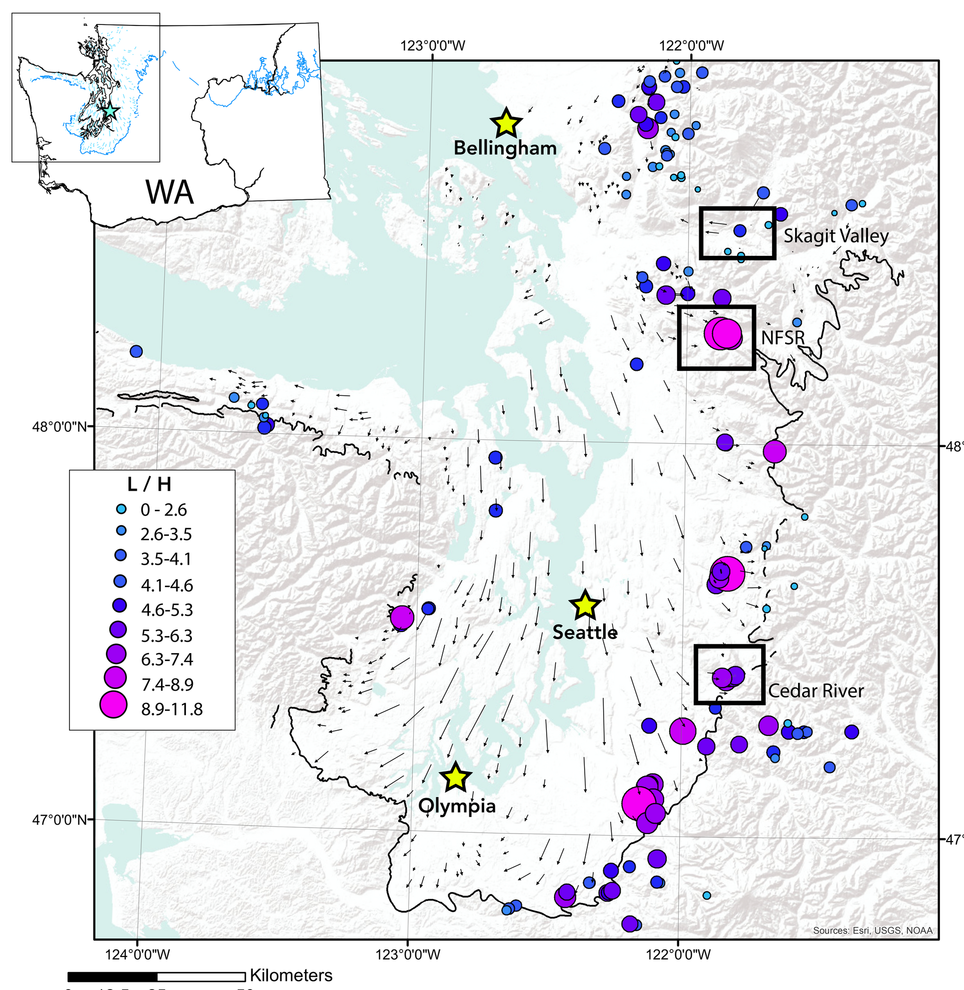
1. What controls the location of large-volume landslides in the glaciated terrain of NW WA?

High-mobility slides cluster toward margins of ice sheet extent

Recent events like the deadly SR 530 (Oso) debris avalanche flow in 2014 brought awareness to landslide hazards within glacial terraces that inundate the valleys of the Puget lowlands and western Cascades. A fundamental question is understanding what controls the spatial variability of such large-volume events in this landscape.

We map ~150 slides from LiDAR data collected by the Puget Sound LiDAR Consortium and measure relative mobility, defined as runout length (L) divided by fall height (H) across a range of lithologies.

High-mobility slides occur in glacial drift deposits within the Puget lowland (black line is ice-sheet extent).

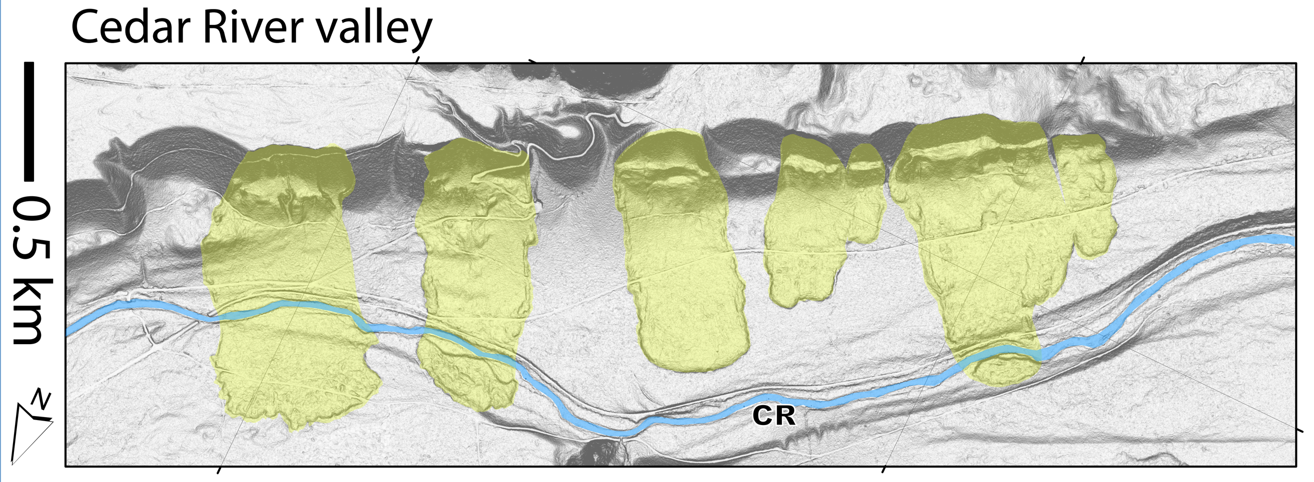


Map of northwest Washington showing landslide relative mobility as colored circles. Black line shows the maximum extent of the Cordilleran Ice sheet at ca. 14 ka. Arrows are subglacial landforms mapped from LiDAR topographic data.

2. Glaciated valleys show different failure styles and sizes

Characteristic landslide volumes in each valley can vary by over an order of magnitude. So what sets this fundamental difference in landslide behavior?

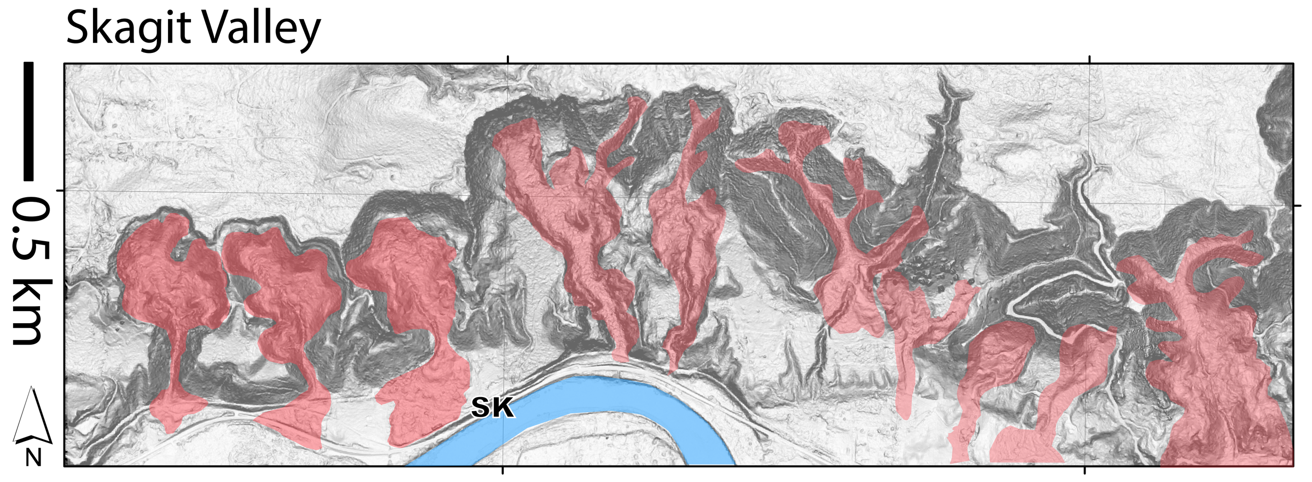
Cedar River valley



Observations

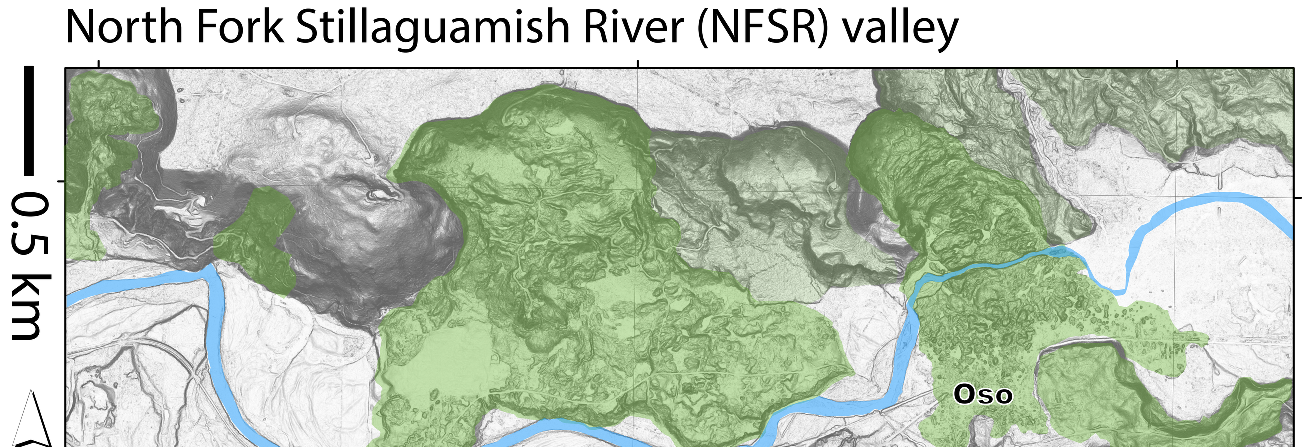
- Tongue-like slides that maintain constant width.
- Levees on slide margins
- Appear to fail along upper slope above bench

Skagit Valley



- Scalloped escarpments, very channelized
- Hourglass shaped failures
- Lower slope scarps that retrogress up channels (many complexes)

North Fork Stillaguamish River (NFSR) valley

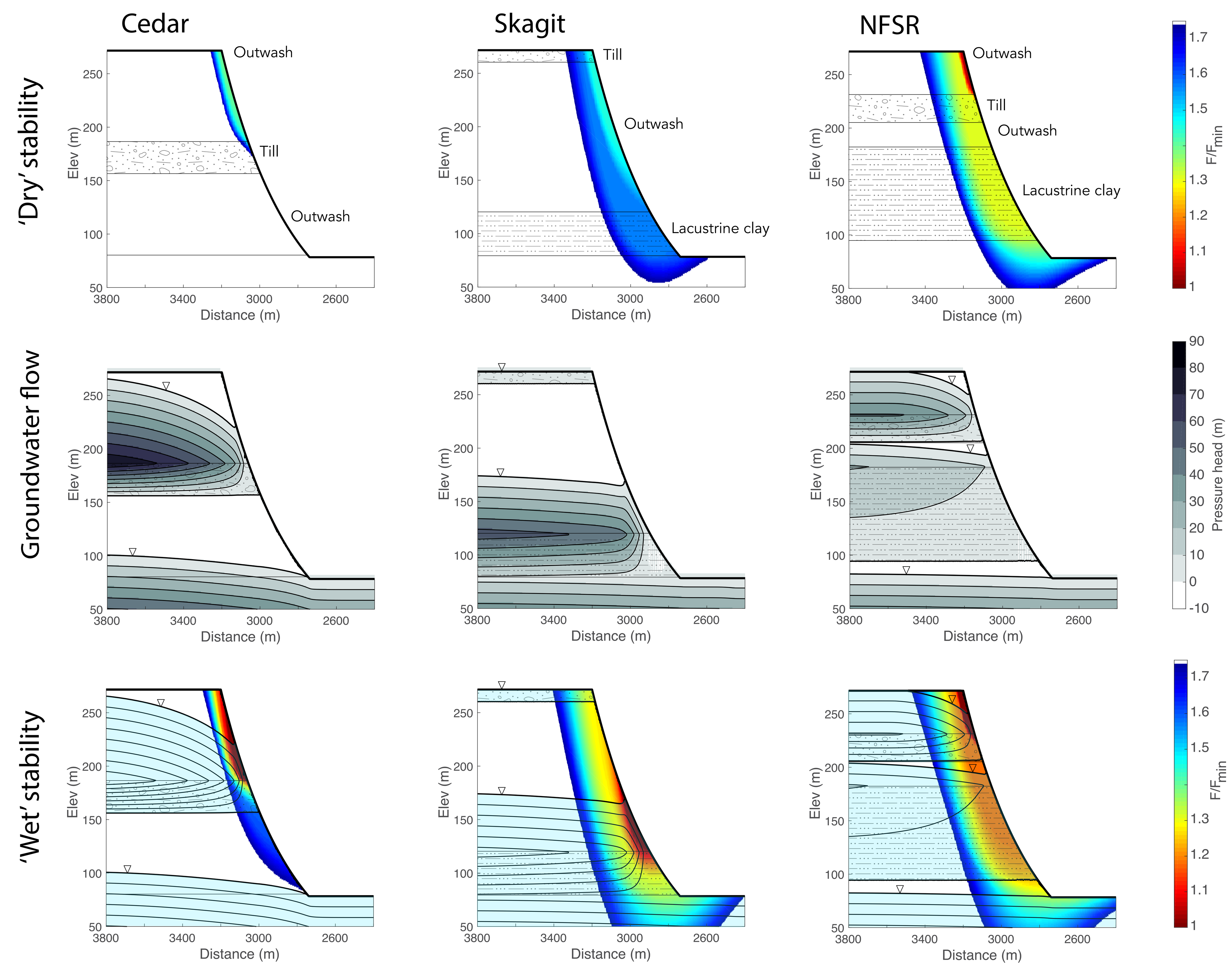


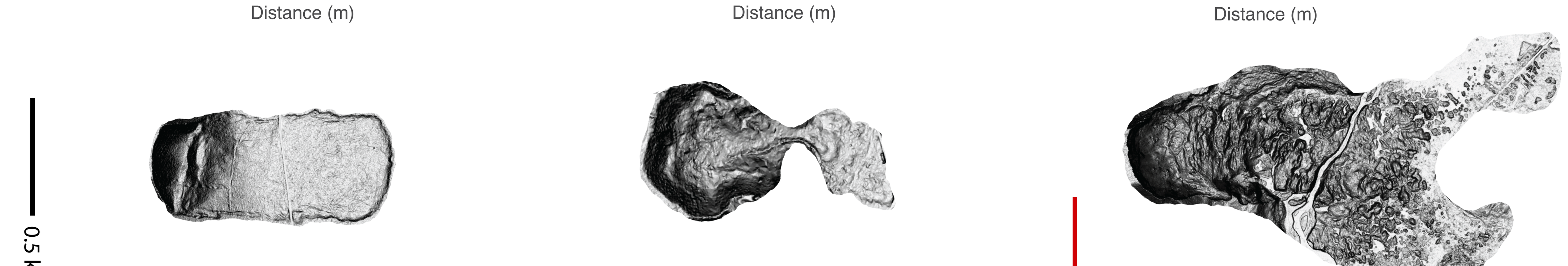
- Abundant large-volume, valley-crossing slides
- Failure of entire hillslope
- Multiple generations of slides preserved

3. How does stratigraphic sequencing affect slope stability?

Hypothesis: variation in stratigraphic sequencing between terraces changes expected slide volume by 1) changing material strength profiles; 2) modulating pore-water pressure distributions

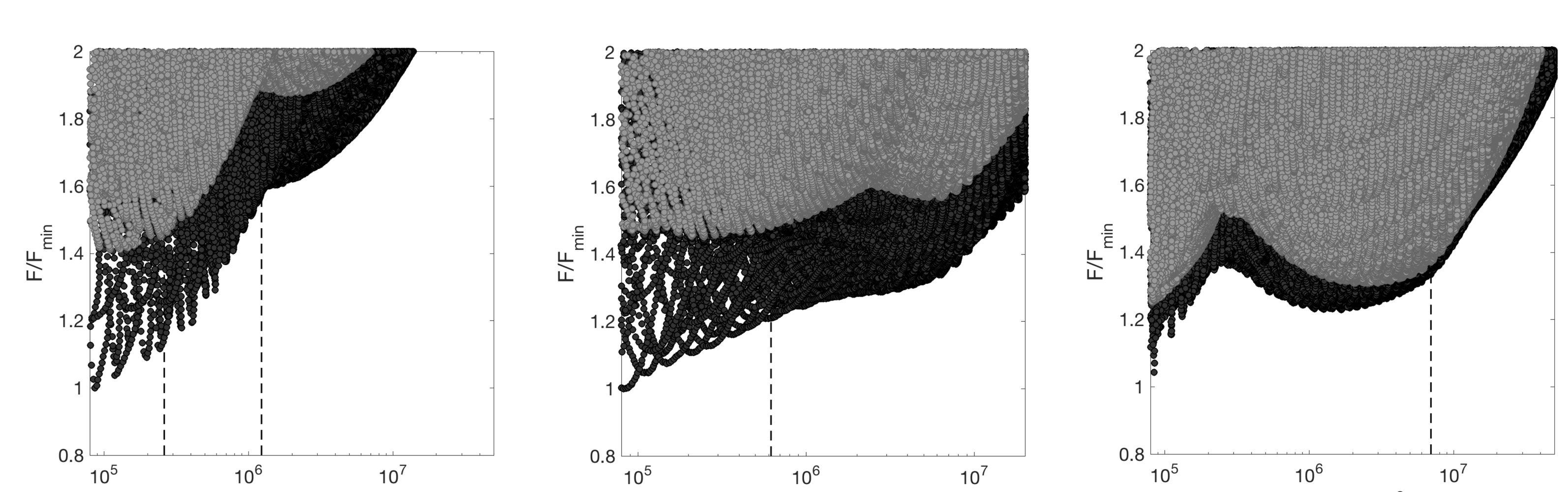
We test the effect of stratigraphic sequencing on predicted landslide volume by coupling a 3D slope stability analysis program (Scoops3D) (e.g., Reid et al., 2015) together with VS2Dt, a 2D variably saturated groundwater flow model (Lappala et al., 1987). We run groundwater simulations to steady state conditions then measure the relative stability patterns and volumes for each configuration.





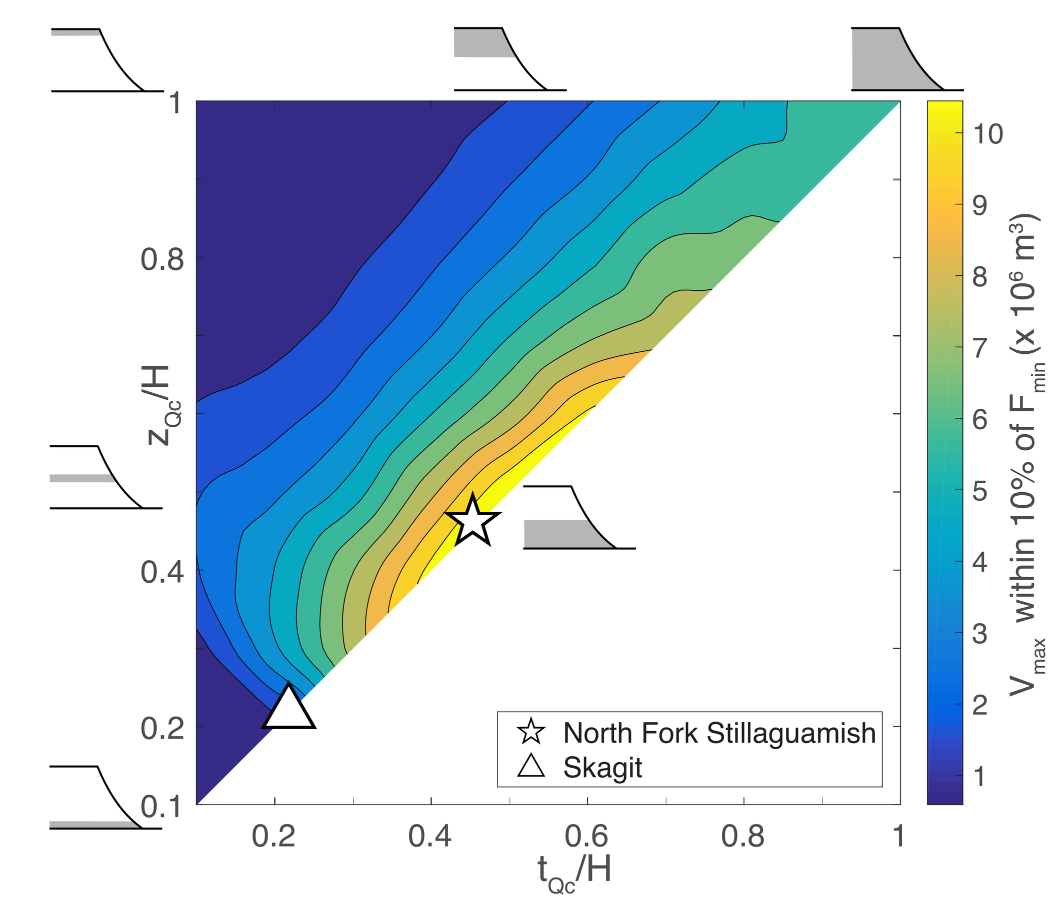
Vol_{CR}: ~9.5 x 10^5 m^3 | Vol_{SK}: ~9.1 x 10^5 m^3 | Vol_{Oso}: ~8.9 x 10^6 m^3

Each terrace shows a unique signature of stability dictated by its stratigraphic configuration. In the Cedar and NFSR cases, the stratigraphic pattern becomes uniformly less stable with groundwater flow. In the Skagit case, this pattern is altered by high pore-fluid pressures at its base.



Left: Plots showing volume and factor of safety for each modeled potential failure plane within Scoops3D. Grey dots are 'Dry' runs and black dots are 'Wet' runs.

4. Slide volumes are higly sensitive to unit thickness and position



We model landslide volumes by varying the position and thickness of a weak clay unit within an outwash terrace, and find that the **largest landslides occur in terraces with 40-60% Qc along their bases like the North Fork Stillaguamish configuration.**

A factor of two increase in Qc thickness leads to an order of magnitude increase in predicted landslide volume

5. Take-home messages

- Glacial terrace stratigraphy exerts a first-order control on failure size and style
- Hydraulic conductivity contrasts significantly alter groundwater flow field, leading to locally high pore-water pressures at contacts
- The thickness and location of weak units within a deposit leads to nonlinear predictions of landslide volume
- Different architectures lead to different failure styles. Morphologic age dating of landslides may require site-specific calibrations even within identical map units.
- Stratigraphic mapping may therefore go a long way toward understanding hazard potential within landforms comprised of layered sediments

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References

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Lappala, E. G., Healy, R. W., & Weeks, E. P. (1987). Documentation of computer program VS2D to solve the equations of fluid flow in variably saturated porous media (pp. 83-4099). Department of the Interior, US Geological Survey.